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APPLIED PHYSICS FOR AIRPLANE MECHANICS

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APPLIED PHYSICS FOR AIRPLANE MECHANICS

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SECTION I

APPLIED MECHANICS

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1. **Force.**—*a. General.*—Force is the action of one body on another tending to change the state of motion of the body acted upon. Force may tend to move a body at rest. It may tend to increase or decrease the motion of a moving body or change its direction of motion. The application of force also may result in one or more of the following states of stress in the body acted upon:

(1) Tension (tendency to make longer or stretch), as in the control cables on an airplane.

(2) Pressure or compression (tendency to shorten or narrow), as on the under surfaces of a wing during a banking maneuver.

(3) Shear (tendency to cut a body by the action of two parallel forces), as in a shaft under a load (example, an automobile axle) or the shearing of a rivet.

b. Measurement.—A force can be measured in three ways: by the weight it can support, by its ability to stretch an elastic body (such as

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a spring), and by its ability to move a body. In aircraft mechanics, force is ordinarily measured in pounds. Less commonly used units of measurement are the gram ([1 gram (g. or gm.) = 0.0353 ounce]) and the kilogram (1 kilogram = 2.204 pounds). Many different instruments have been designed for both manual and automatic measurement of force in aircraft.

c. Resultant forces.—If a force or forces are applied to a moving body, the body will tend to move at a different speed or in a different direction, or both. The force resulting from the combined action of two or more forces is called the "resultant."

(1) If two forces applied to a point act in the same direction, the resultant will be a force equal to the sum of the two forces and will act in the same direction. Thus, if a northward force of 10 pounds and a northward force of 15 pounds act on a point, the resultant will be a northward force of 25 pounds.

(2) If two forces applied to a point act in opposite directions, the resultant will be a force equal to the difference between the two forces and will act in the direction of the larger force. Thus, if a northward force of 10 pounds and a southward force of 15 pounds act on a point, the resultant will be a southward force of 5 pounds.

(3) If a force is applied to a point at an angle to another force acting on the same point, the resultant will be a force of a magnitude that depends on the size of the angle between the two forces and on their magnitudes. This resultant will act in a direction nearer that of the larger force. The direction and magnitude of the resultant can be determined graphically by representing the two forces as adjacent sides of a parallelogram, with the length of the sides drawn in proportion to the magnitude of the forces. The length of the diagonal of the parallelogram will represent the resultant. Thus, in figure 1 ①, the

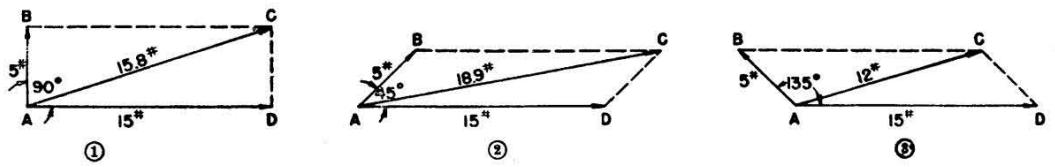


FIGURE 1.—Resultants.

resultant of force AB (5 pounds) and force AD (15 pounds) meeting at right angles is a force of about 15.8 pounds acting in the direction AC. In figure 1 ②, in which forces AB and AD act at an angle of 45°, the resultant acts in a different direction and is of greater magnitude than in figure 1 ①. In figure 1 ③, in which forces AB and AD act at an angle of 135°, the resultant acts in still another direction and is of smaller magnitude.

2. Force of gravity.—*a. General.*—Every body of matter in the universe attracts every other body with a certain force. This force is called "gravitation." The term "gravity" is used to refer to the force which tends to draw all bodies toward the center of the earth. The weight of a body is the resultant of all gravitational forces acting on the body.

b. Center of gravity.—Every particle of an object is acted on by the force of gravity. However, in every object there is one point at which a single force, equal in magnitude to the weight of the object and directed upward, can keep the body at rest—that is, can keep it in balance and prevent it from falling. This point is known as the "center of gravity." The center of gravity might be defined as the

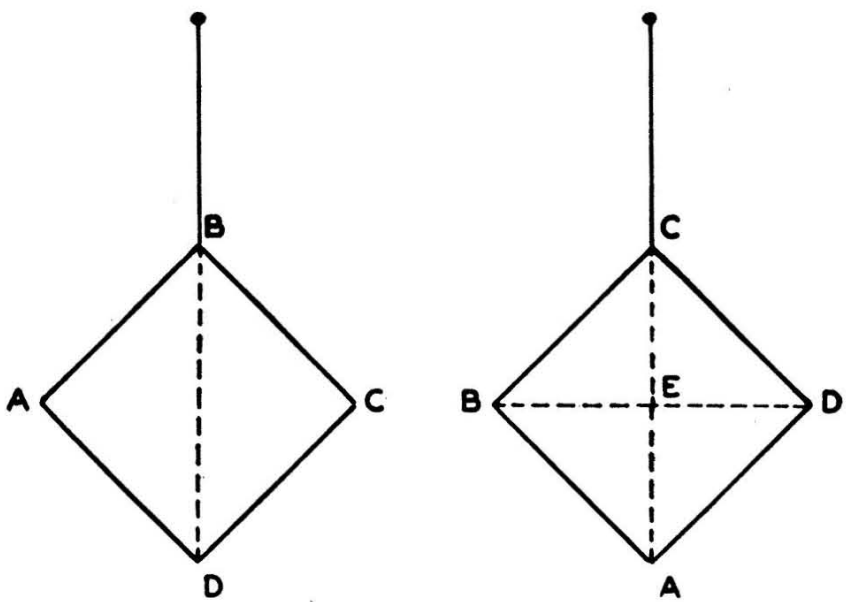


FIGURE 2.—Location of center of gravity.

"point at which all the weight of a body may be considered concentrated." Thus, the center of gravity of a perfectly round ball would be the exact center of the ball, and the center of gravity of a ring would be the center of the ring—not any point in the ring itself. Likewise, the center of gravity of a cube would be a point within the cube equidistant from all eight corners. In airplanes, ease of control and maneuverability depend partly on the location of the center of gravity.

c. Location of center of gravity.—Since the center of gravity of a body is that point at which its weight may be considered to be concentrated, the center of gravity of a freely suspended body will always be vertically beneath the point of support. To locate the center of gravity, therefore, it is necessary only to determine the point of intersection of vertical lines drawn downward from two points of support on the body. Thus, in figure 2, if the flat object ABCD is suspended

first from point B and then from point C, the intersection E of the lines BD and CA is the center of gravity. The center of gravity of any irregular three-dimensional body could be determined in the same way.

3. Laws of motion.—*a. Inertia.*—An object at rest tends to remain at rest, and an object in motion tends to remain in motion in a straight line, unless an external force is applied to change the state of rest or motion of the object. Inertia is *that property of an object which tends to keep it at rest or in motion in a straight line.* Thus a stationary airplane remains stationary until force is applied to move it, while a gliding airplane tends to keep gliding until the force of friction with the air, gravity, and other forces end its flight. Force is always required to change the state of motion of any body.

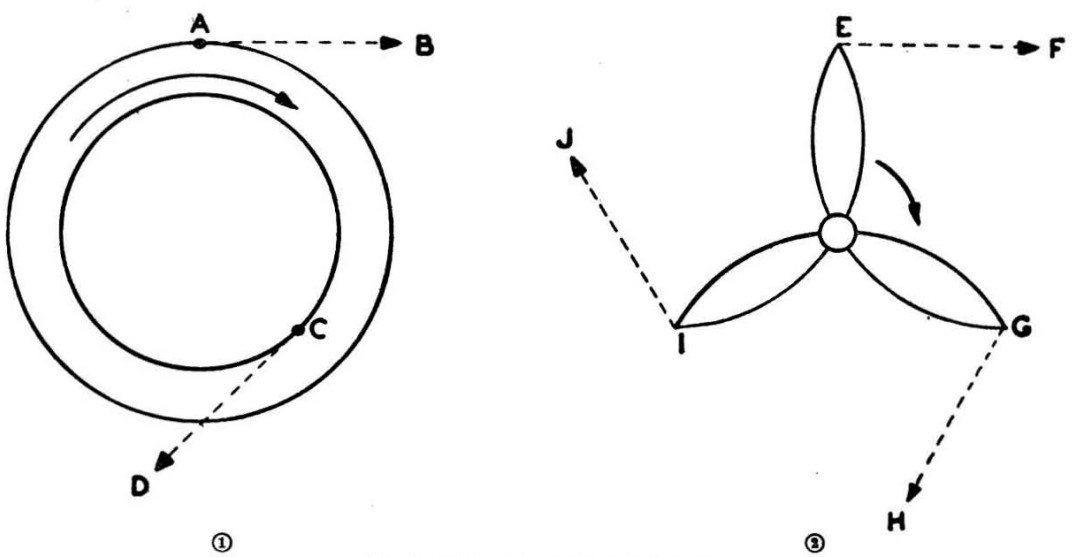


FIGURE 3.—Centrifugal force.

b. Centrifugal force—definition.—The tendency of a moving body to keep moving in a straight line is the reason an airplane "skids" when making an improperly banked turn, why mud flies from a rotating automobile tire, etc. All parts or rotating objects are subject to this force, which is known as "centrifugal force." Centrifugal force may be defined as the "force with which any part of a rotating body tends to fly outward at a tangent to the circle of its rotation."

(1) *Examples.*—Centrifugal force is present in a whirling flywheel or a rotating propeller. In figure 3① the point A on the revolving wheel tends to fly outward along the tangent AB, while the point C tends to fly outward along the tangent CD. In figure 3② representing a rotating propeller, the point E tends to follow the tangent EF, G the tangent GH, and I the tangent IJ.

(2) *Magnitude.*—Rotating parts which are fixed cannot fly outward; therefore, stresses due to centrifugal force are set up within them. The greater the speed and the greater the weight of the rotating part, the greater the centrifugal force exerted. Thus, in figure 3① point A moves faster than point C because it is farther from the axis of rotation; hence the centrifugal force at point A is greater than that at point C. Many parts of aircraft, such as the propeller hub, are subjected to centrifugal loads. These parts must have great strength in order to withstand the loads exerted.

c. Momentum.—The quantity of motion possessed by a moving body—that is, the force with which it moves—is its "momentum." The momentum of a body is equal to the product of its mass (weight) and its velocity (speed); or, in the form of an equation:

$$\text{Momentum} = \text{mass} \times \text{velocity}.$$

Thus a body weighing 10 pounds and moving at the rate of 10 feet per second has a momentum of 100 pounds-feet per second.

4. Work.—*a. General.*—Any force which changes the state of motion of a body is performing work upon that body. The amount of work accomplished is equal to the product of the force applied to the body and the distance through which it is moved, providing the displacement is in the direction of the force. Thus, if a body weighing 2 pounds is lifted 8 feet, 16 foot-pounds of work is done. If a force acts upon a body at rest without moving it, no work is said to be done (although it may be said that a force is exerted on the body). When a body is being moved across a horizontal plane, the only work done is the work necessary to overcome the friction between the body and the plane.

b. Measurement.—In aircraft mechanics, the inch-pound and the foot-pound are the commonly used units for measuring work. An inch-pound is the work done by a force of 1 pound acting through a distance of 1 inch, and a foot-pound is the work done by a force of 1 pound acting through a distance of 1 foot. A mechanic who lifts a weight of 50 pounds to a height of 3 feet accomplishes 150 foot-pounds of work.

5. Efficiency.—*a. General.*—No machine operates with perfect efficiency. In all machinery, the work expended is always greater than the work accomplished, because some of the work is converted into heat by friction, compression, and collision among the parts. The efficiency of a machine is the ratio of the total work accomplished to the total work expended, thus:

$$\text{Percent efficiency} = \frac{\text{work accomplished (output)} \times 100}{\text{work expended (input)}}$$

b. Efficiency of some simple machines.—Machines vary a great deal in efficiency. A simple lever, in which the friction of the lever against a knife-edge fulcrum is very small, may have an efficiency of nearly 1; that is, it may be almost 100 percent efficient. The common block and tackle with several pulleys may have an efficiency of only 40 to 60 percent, much of the work expended being wasted in overcoming the friction of the rope on the pulleys and of the pulleys on their axes of rotation. A system of gears may have an efficiency as high as 95 percent. Heavier and more complicated machinery, such as steam and internal-combustion engines, is much less efficient because of the large amount of work converted into heat by friction and compression.

6. Pulleys.—*a. General.*—The use of pulleys to facilitate the accomplishment of work is familiar to everyone. A pulley system is

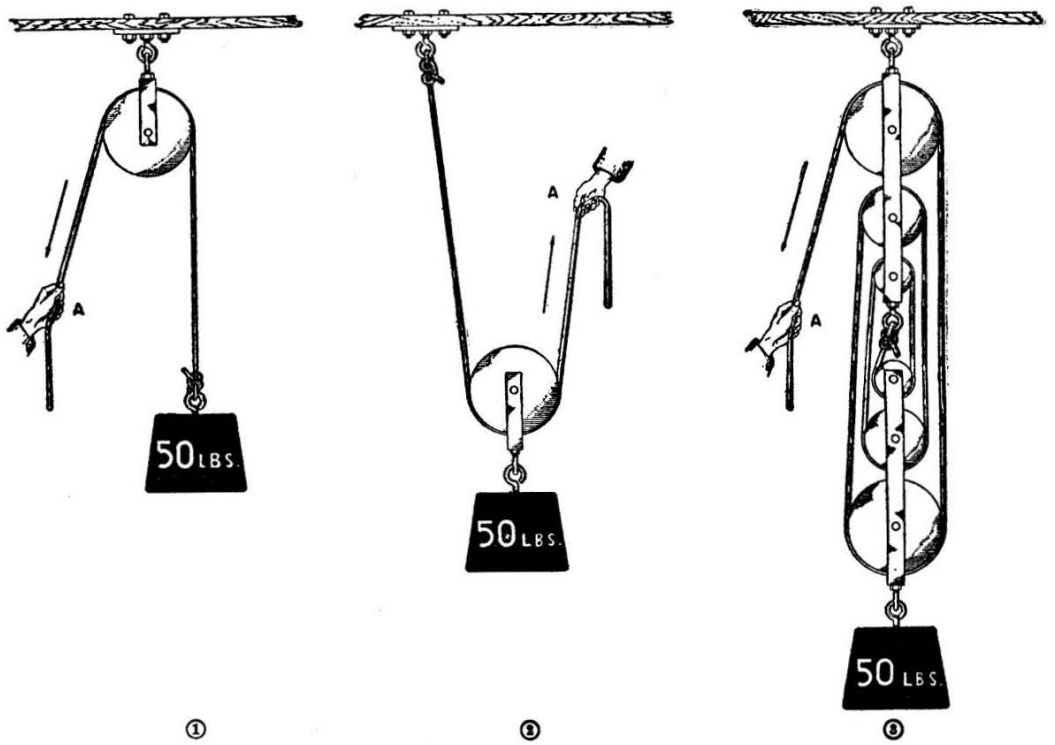


FIGURE 4.—Pulleys.

a device by which a given force can be increased by reducing the distance through which it operates, or vice versa. In other words, by means of a pulley system, force can be increased at the expense of distance, or distance at the expense of force. The total amount of work, however, remains constant. Thus, a man lifting a weight of 50 pounds to a height of 1 foot with his hand must exert a force of 50 pounds and does 50 foot-pounds of work. The same man, by using the single movable-pulley system shown in figure 4②, could lift

50 pounds 1 foot by exerting a force of 25 pounds through a distance of 2 feet, in which case he would still be doing 50 foot-pounds of work. By using several pulleys in a single system, a large force can be exerted through a short distance by the exertion of a small force through a long distance, or vice versa. In aircraft, the principle of the pulley is used in the automatic pilot for moving the control surfaces, etc.

b. Examples.—In figure 4①, note that a force of 50 pounds must be applied downward at A to lift the weight of 50 pounds, which moves through the same distance as the force exerted. In figure 4②, a force of 25 pounds applied upward at A will raise the weight a distance equal to half the distance through which the force is exerted. In figure 4③, a force of 8⅓ pounds applied downward at A will raise the weight a distance equal to one-sixth of the distance through which the force is exerted. In all three cases, the total amount of work done remains the same (force exerted × distance exerted; or, weight moved × distance moved).

c. Efficiency.—In the examples just given, perfect efficiency of the pulley systems was assumed. Actually, the force of friction and the force required to overcome the inertia of the stationary weight would necessitate the application of a greater force to do the work.

d. Mechanical advantage.—When, as with a pulley system, a force is used to overcome a larger resisting force, a *mechanical advantage* is said to have been gained. Mechanical advantage is equal to the resistance overcome divided by the force exerted. Thus, the theoretical mechanical advantage (ignoring friction) of the single fixed pulley is 1; of the single movable pulley, 2; and of the combination of six pulleys, 6. If, in figure 4③ the weight were placed at A and the force exerted where the weight is now attached, the mechanical advantage in force would be 1/6, since a force of 300 pounds would have to be exerted to lift the weight (through a distance six times the distance through which the force was exerted). If distance or speed is gained instead of force, the mechanical advantage is equal to the distance the resistance is moved divided by the distance the effort moves.

7. Levers.—*a. General.*—Like the pulley, the lever is used to gain mechanical advantage—to gain force or distance, one at the expense of the other. A lever is essentially a rigid rod free to turn about a point P called the "fulcrum." (See fig. 5.) Wrenches, crowbars, and scissors are examples of levers.

b. Classification of levers.—There are three types of levers. In the first type (fig. 5①), the fulcrum P is located between the applied effort E and the resistance R. In the second (fig. 5②), the resistance R is between the fulcrum P and the effort E. In the third (fig. 5③),

the effort E is between the resistance R and the fulcrum P. Note that in figure 5① the nearer the resistance is to the fulcrum, the less will be the effort required to overcome it; and the farther the resistance is from the fulcrum, the more will be the effort required to overcome it. The same is true in figures 5② and 5③. Figures 5① and 5② represent types of levers with which force is gained at the expense of distance, while figure 5③ represents a lever with which distance is gained at the expense of force.

c. Moments—definition.—If, in figure 5①, the resistance R equals 4 pounds and it is 2 inches from the fulcrum P, and if the effort E is applied 8 inches from the fulcrum, it will be found that an effort of 1 pound will balance the resistance R. In other words, when a lever is balanced, the product of the effort and its lever arm (distance from the fulcrum) equals the product of the resistance and its lever arm.

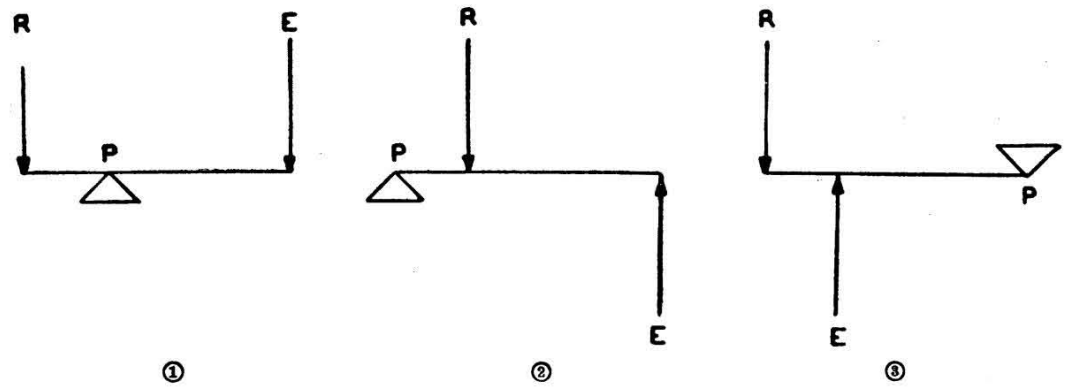


FIGURE 5.—Types of levers.

The product of a force and its lever arm is called the "moment" of that force.

Example: If, in figure 5②, the lever arm of the effort E is 8 inches, and the effort E equals 2 pounds, the moment of the effort E will be 16 inch-pounds. Likewise, if in figure 5②, the resistance R equals 8 pounds and its lever arm is 2 inches, the moment of the resistance R is 16 inch-pounds, and the lever is in balance.

d. General law of the lever.—From the foregoing examples, it can be seen that the general law of levers is as follows: *If a lever is in balance, the sum of the moments tending to turn the lever in one direction about an axis equals the sum of the moments tending to turn it in the opposite direction.* Thus, if several different efforts are applied to a lever, the sum of the moments of resistance will equal the sum of the moments of effort (if the lever is balanced).

e. Work done by levers.—Whenever a lever is used to do work, the work accomplished is always equal to the product of the resistance and the distance through which it is moved. Thus, if a weight of 10

pounds is lifted 2 feet by means of a lever, the work accomplished is 20 foot-pounds. Note that the work accomplished equals the sum of the moments of the resistance and also (ignoring friction) equals the sum of the moments of the effort expended.

f. Mechanical advantage.—As with pulleys, the mechanical advantage of a lever is equal to the sum of the resistance overcome divided by the sum of the efforts expended. Thus the mechanical advantage of the lever in figure 5① is 4. As with pulleys, the efficiency of a lever is always reduced by friction and often by other incidental forces tending to interfere with the functioning of the mechanism.

8. Gears.—*a. General.*—A gear is a wheel which has teeth designed to mesh with the teeth of a similar wheel, to which or from which motion may be transmitted. A set of gears is another device by which mechanical advantage can be gained. Gear systems are essentially systems of levers. They are used in many parts of an airplane—in the engine, in some pumps, etc.

b. Examples.—In figure 6①, assume that gear A receives clockwise motion from the drive shaft P. Gear B, with which gear A is meshed, is caused to turn in a counterclockwise direction. But since gear A has twice as many teeth as gear B, gear B will revolve twice for each revolution of gear A. In other words, by means of gear A, a mechanical advantage in speed of 2 (two revolutions of gear B per single revolution of the turning shaft) is gained. In this case, speed (in gear B) is gained at the expense of force (in the shaft to which gear B is attached).

(1) In figure 6②, gear B is turned by a shaft P, and gear A is turned by gear B. Gear A turns only one-half revolution per single revolution of the shaft, and the mechanical advantage in speed is 1/2. In this case, the force delivered by the shaft to which gear A is attached will be twice the force applied to shaft P, and the mechanical advantage in force will be 2. Thus force is gained at the expense of speed.

(2) Systems of gears of various sizes can be devised to perform many kinds of mechanical work. In the aircraft engine accessory section, for example, systems of gears connected to the crankshaft are used to drive the different accessories at different speeds.

9. Friction.—*a. General.*—Whenever one object is slid or rolled over another, irregularities in the contacting surfaces interlock and so cause a certain amount of resistance to the force exerted. This kind of resistance is known as "friction." Even the rubbing together of two pieces of ice would produce friction, though in this case the friction would be much less than in the rubbing together of two rough stones. Likewise, friction exists in the contact of air with all

parts of an airplane in flight. Friction is always present in machinery, and accounts partly for the fact that the work accomplished by a machine is never as much as the effort or energy exerted. Work done against friction is wasted. However, friction can be reduced by minimizing the necessary contacts of moving parts, by making contacting surfaces as smooth as possible, by the use of bearings, and by the use of lubricants.

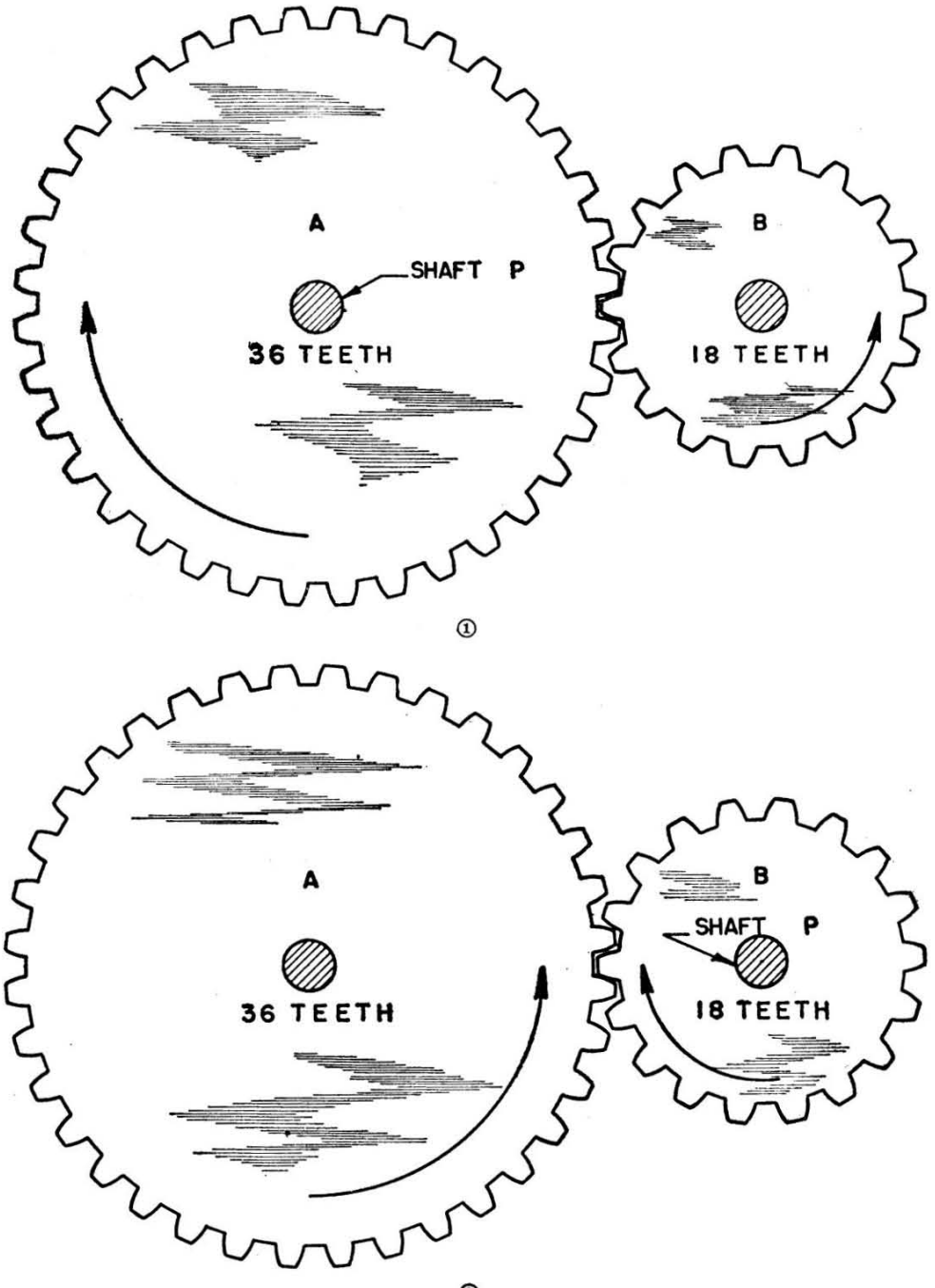
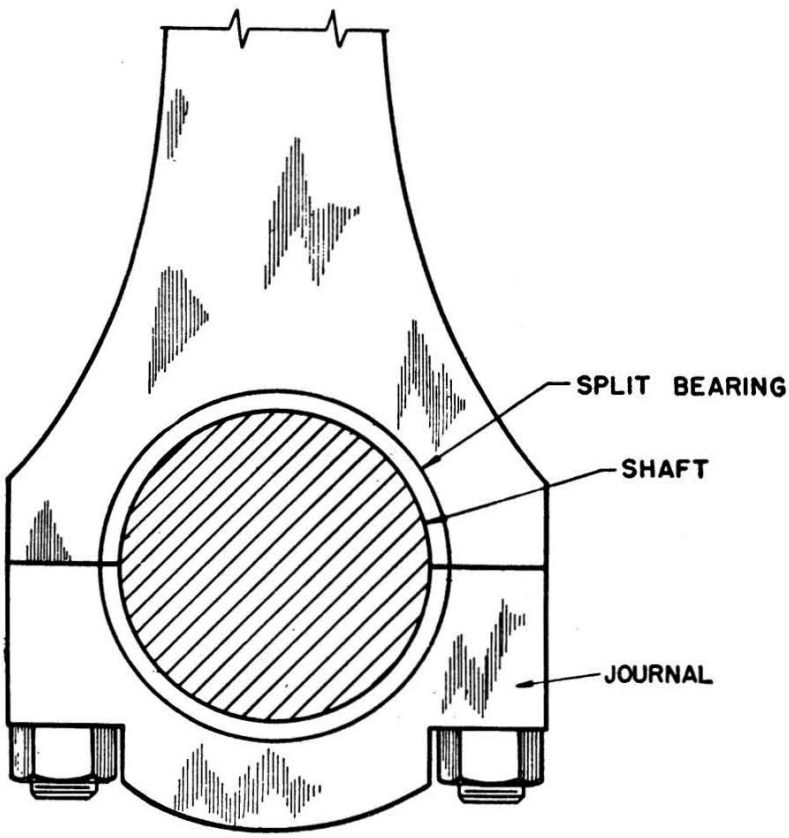


FIGURE 6.—Gears.

b. Kinds of friction.—There are two kinds of friction: sliding and rolling. Sliding friction is usually much greater than rolling friction. When one object is rolled over another the irregularities of the contacting surfaces obviously cause less resistance than if the two objects were rubbed against one another. Where practicable, devices are used in machinery to convert sliding friction into rolling friction.

c. Bearings.—To reduce the amount of work wasted in overcoming friction (and to reduce wear), devices called "bearings" are used where



① Common bearing.

FIGURE 7.—Bearings.

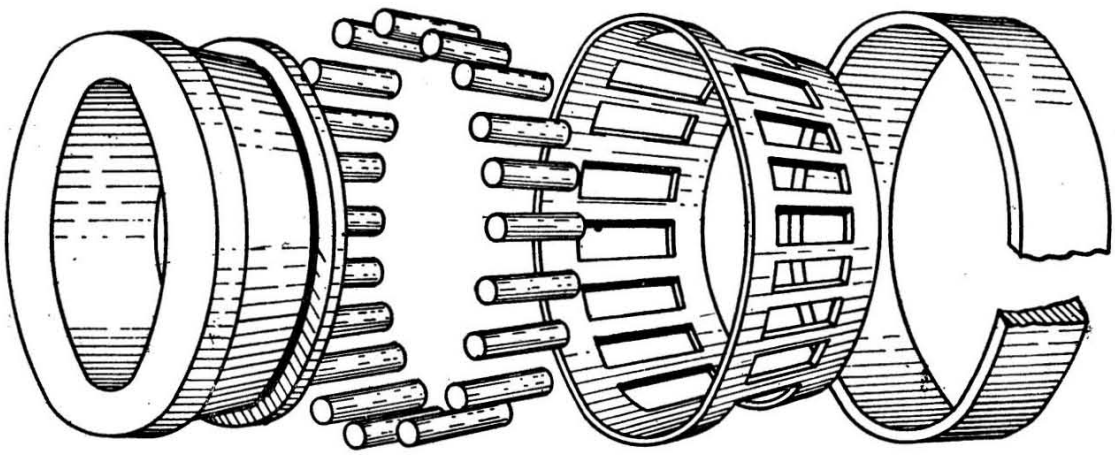
moving parts contact each other. Bearings are of three general types: common or friction, ball, and roller. The ball and roller types convert sliding friction into rolling friction. Oils, greases, and other lubricants are used to further reduce friction.

(1) In the common type bearing (fig. 7 ①), the shaft rotates in the journal. The journal is lined with some bearing metal such as babbitt, white metals, lead bronzes, etc., to reduce friction. Lubrication of this type of bearing supplies a film of oil between the shaft and bearing metal which further reduces friction.

(2) Roller bearings (fig. 7 ②) are used where heavy loads must be supported. A roller bearing consists of a cone (inner race), a set

of rollers, a cage, and a cup (outer race). The rollers, which are mounted between the inner and outer races, are held in place by the cage. They may be cylindrical or conical in shape. Rollers and races are made of very hard steel. The inner race is mounted on the shaft and turns with it. As the inner race is turned, the rollers rotate between the races and change sliding friction to rolling friction.

(3) Ball bearings are used where comparatively light loads are carried by the bearing. A ball bearing is similar in construction and operation to a roller bearing. Steel balls are used instead of rollers.



② Tapered roller bearing—exploded view.

FIGURE 7.—Bearings.—Continued.

One or two rows of balls may be used. The inner race is mounted on the shaft and turns with it. As this race turns, the balls roll between it and the outer race. Thus practically all sliding friction is changed to rolling friction.

SECTION II

HEAT

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10. General.—*a. Generation of heat.*—When a hole is being drilled in a piece of wood or metal, it is noticed that a certain amount of heat is generated; that is, the temperature of the drill and the object being drilled rises. Likewise, when a lead bullet strikes heavy armor plate,

so much heat is generated that the lead melts almost instantaneously. It is also noticed that when a gas is compressed (such as air being pumped into a tire), it is warmed. Finally, everyone has noted that when an object burns (unites with oxygen), considerable heat is given off. From these four examples it is apparent that heat can be generated in four ways: by friction, collision, compression, and chemical reaction.

b. Generation of heat in aircraft engines.—In an operating aircraft engine, heat is generated by sliding or rolling contact of moving parts (friction), by the action of pistons on the fuel-air mixture (compression), and by the combustion of gasoline (chemical reaction). Heat may also be produced by collision of some of the parts. The generation of this heat presents certain problems which the engine designer must solve if the engine is to operate efficiently.

11. Definition of heat.—Heat may be regarded as the energy of motion of the molecules (tiny particles) that make up an object. The energy of the molecules of any object can be increased by friction, collision, compression, or in some cases, chemical reaction. Their energy can be increased also by contact with, or nearness to, the molecules of a warmer object, that is, an object in which the molecules are moving faster. The ways in which heat is transferred from one object to another are explained in paragraph 16.

12. Measurement of heat.—*a. Definition of temperature.*—When an object is hot, it is said to have a "high temperature"; when it is cold, it is said to have a "low temperature." Temperature is the relative state of hotness or coldness of the object being discussed. Or, as already indicated, it is the relative energy of motion of the molecules that make up the object; the faster the motion of the molecules, the higher the temperature, and the slower the speed of the molecules, the lower the temperature.

b. Thermometers.—Most substances have a tendency to expand as they grow warmer and contract as they grow cooler. Temperature can therefore be easily measured by the expansion and contraction of any substance the volume of which changes proportionally within certain temperature limits. Any device containing such a substance and used to measure temperature is a thermometer. The substance most commonly used in liquid thermometers is mercury, since it is a liquid which changes proportionally in volume according to temperature changes and has a low freezing point (−39° C.) and a high boiling point (357° C.). When very low temperatures are to be measured, thermometers containing alcohol (freezing point −130° C.) instead of mercury are often used. Various other kinds of thermometers have been developed for special purposes—

(1) The vapor-pressure thermometer contains a highly volatile liquid which vaporizes or condenses (and thus exerts varying pressures on an indicator) according to changes in temperatures.

(2) In the resistance type of thermometer, the variations of the resistance of an electrical conductor indicate temperature changes.

(3) In the thermocouple thermometer, the registered difference between the electrical potentials of two different metals indicates temperature.

(4) In the bimetallic thermometer, temperature is indicated by the difference between the amounts of expansion of two metals.

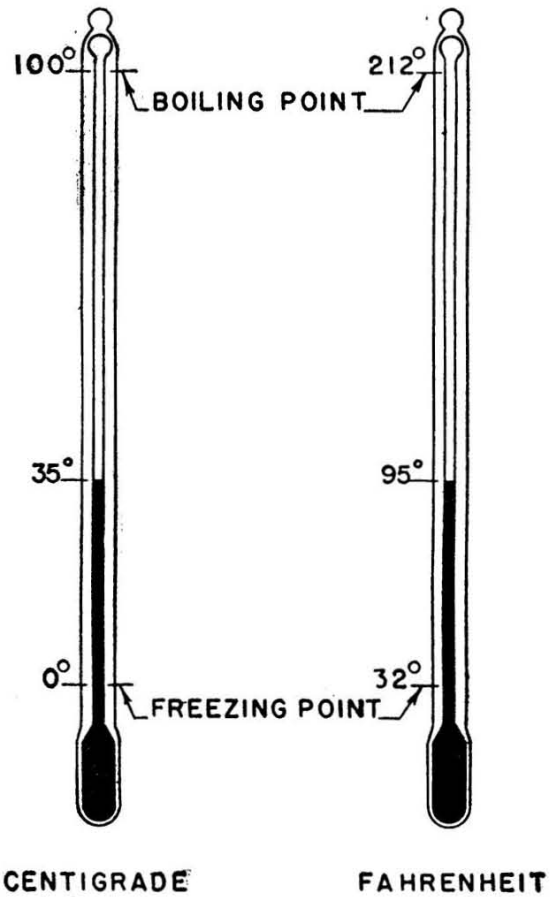


FIGURE 8.—Thermometers.

c. Centigrade and Fahrenheit scales.—(1) *Description.*—The two most commonly used scales for the graduation of thermometers are: centigrade (C.) and Fahrenheit (F.). On the centigrade scale the temperature of melting ice (freezing point) at sea level is marked "0°," and the temperature of boiling water (boiling point) at sea level, "100°." On the Fahrenheit scale the corresponding markings are "32°" and "212°." The centigrade scale is most used in connection with the metric system and in scientific work. Both scales are widely used in the United States. Figure 8, illustrating centigrade

and Fahrenheit thermometers side by side, shows their comparative readings.

(2) *Conversion.*—When it is desired to convert a reading on one scale into a reading on the other, the following simple formulas can be used:

$$C.=5/9\ (F.-32).$$
$$F.=(9/5)\ C.+32.$$

Thus, to find the centigrade equivalent of 50° F.: $C.=5/9\ (50-32)=5/9\ (18)=10°$. To find the Fahrenheit equivalent of −10° C.: $F.=9/5\ (-10)+32=14°$.

13. Units of heat.—For convenience, the standard unit of heat has been taken as the amount of heat required to raise the temperature of a unit quantity of water a given number of degrees according to a given temperature scale. The two most commonly used units of heat are the calorie and the British thermal unit (Btu). A calorie is the amount of heat required to raise the temperature of 1 gram of water 1° C. (centigrade). A Btu (252 calories) is the amount of heat required to raise the temperature of 1 pound of water 1° F. (Fahrenheit).

14. Mechanical equivalent of heat.—Whenever work is done, the *useful* work accomplished is never as much as the work expended. For instance, if the efficiency of a pulley system is 50 percent, this means that the work expended is twice as great as the useful work accomplished; that 50 percent of the effort is used to overcome friction. This wasted effort is converted into heat. Likewise, whenever work of any kind is done, either friction, collision, compression, or chemical reaction is involved and heat is generated. By experiment it has been proved that a calorie is equal to 427 gram-meters of work (a force of 427 grams exerted through a distance of 1 meter), and that a Btu is equal to 778 foot-pounds of work.

15. Heat conductivity.—At any given temperature, certain objects feel warmer than others. This difference is due to the difference between the heat conductivities of the substances involved. The heat conductivity of a substance is its ability to conduct or absorb heat. Most metals are good conductors of heat (and hence at room temperatures feel cool to the touch); gases are very poor conductors. Wood and liquids are poor conductors, and certain kinds of stone are good conductors. The heat conductivity of any substance depends on its molecular structure and on the state in which it occurs.

16. Transfer of heat.—*a. Types of heat transfer.*—Heat can be transferred within an object or from one object to another. Heat transfer by contact is known as "conduction." Heat transfer by proximity (nearness) occurs by a process known as "radiation." In

most cases of heat transfer, both of these processes are occurring, and *heat is transferred always from the warmer object to the cooler object*, never the reverse. A third process of heat transfer, involving the movement of a heated mass of gas or liquid from one place to another in a larger mass of gas or liquid, is called "convection."

b. Conduction.—Heat has already been described as the energy of motion of the molecules of an object. When the cooling liquid in an aircraft engine comes into contact with a hot cylinder wall, the molecules of the objects strike against one another and part of the high energy of motion in the molecules of the cylinder wall is transferred to the liquid. In this way the cylinder wall is cooled and the liquid is warmed. Similarly, the air rushing around an air-cooled engine during flight is warmed and the engine is cooled. Both of these examples illustrate the process of conduction.

c. Radiation.—If the hand is held at a distance from any very hot object, heat is felt, although the intervening air may be cold. In the same way the sun transmits heat to the earth without any intermediate medium above the earth's atmosphere. Such heat will pass through clear glass without warming it. When heat is transferred in this way it is said to be radiated. Thus an aircraft engine in operation is constantly transferring heat to its surroundings not only by conduction (by means of contact with the air and the coolant), but by radiation—a process in which objects at a distance are somewhat warmed but the intervening air is not appreciably warmed.

d. Convection.—Most substances expand when heated and thus become lighter per unit of volume. Water at the bottom of a kettle over a fire rises as it is heated, and the cooler water at the top of the kettle descends. Air passing over a hot stove likewise rises. In each case the heated fluid rises because it is lighter per unit of volume than the surrounding unheated fluid. Heat can therefore be transferred from one place to another by the tendency of a heated mass (of liquid or gas) to rise. This process is known as "convection." It is illustrated in the operation of airplane-cabin heating units, the heat from which is distributed to a considerable extent by convectional air currents. Currents of hot air rise and currents of cool air descend in directions determined by the locations of heater outlets and like factors.

17. Conditions of heat transfer.—*a. In conduction.*—The speed with which heat is transferred to or from one substance in contact with another substance depends on the heat conductivities, area of contact, and temperature differences of the substances involved. Heat will pass very slowly from a warm block of wood to a cool block of wood laid against it; it will pass rapidly from a warm block of metal

to a cool one laid against it. It will pass slowly from wood to metal or metal to wood, and still more slowly if only the corners (small areas) of the blocks touch. Obviously, the transfer of heat will be more rapid if the temperature difference between the blocks is great than if this difference is small.

b. In radiation.—Various substances radiate heat or absorb radiated heat with varying degrees of speed. As with conduction, the speed of radiation depends to some extent on the conductivities of the substances involved, on the areas exposed, and on the difference between their respective temperatures. To illustrate, metal radiates heat or absorbs radiated heat faster than wood; a rough surface radiates heat or absorbs radiated heat faster than a smooth surface (because roughness represents more area); and a hot object radiates heat faster to a cold object than a warm object would radiate it. Radiation also depends on the color of the surface involved. If a given substance has a dark surface, it will radiate more heat and absorb more radiated heat than if it has a light surface. This is true because a light surface tends to reflect heat. Thus a polished sheet of aluminum will radiate or absorb relatively less heat than a sheet with a dark-painted surface. Likewise, a heater with a dark case would radiate more heat than one with a light-colored case.

c. In convection.—The transfer of heat by convection depends on the speed of motion, the quantity, and the heat conductivity of the substance. Air-cooled engines are cooled not only by conduction (contact of air and oil with the hot engine) and radiation, but by convection (circulation of oil and the passage of air to, over, and from the engine). The more rapid the circulation of the air, the more rapid the cooling. Liquid-cooled engines similarly are cooled partly by convection (circulation of oil and the passage of the coolant through the cooling system). Again, the greater the quantity and the more rapid the circulation of the oil and the coolant, the more rapid the cooling effect. In an aircraft engine the design of the cooling system is based partly on the calculation of convectional factors involved. Likewise the design of any air heating system will involve calculations as to directions, speeds, and quantities of air to be circulated.

18. Changes of state.—*a. General.*—When a substance is changed to or from the form of solid, liquid, or vapor, it is said that a "change of state" takes place. The melting of ice and freezing of water, the evaporation of gasoline, the condensation of water vapor in the atmosphere, are all examples of change of state. In all changes of state, heat is involved, being absorbed or given off in certain quantities determined by the properties of the substances, temperatures and, in some cases, pressure conditions.

b. Fusion.—Fusion or "melting" is the change of state from solid to liquid. The temperature at which any substance melts depends on its molecular structure; that is, on the amount of heat that must be applied to speed up the motion of its molecules to such an extent that the substance passes from the solid to the liquid state. Thus the melting point of ice is 32° F. (0° C.). The amount of heat required to change merely the state of a substance from solid to liquid without changing its actual temperature is the "heat of fusion." The heat of fusion of ice is 80 calories per gram, since 80 calories of heat are required to change a gram of ice at 32° F. to water at 32° F.

c. Solidification.—Solidification is the reverse of fusion. It is the change of state from a liquid to a solid. During this change from a liquid to a solid at the same temperature, the same amount of heat is given off as it takes to change the substance from a solid to a liquid.

d. Evaporation.—Evaporation is the change of state from liquid to vapor. When a liquid is evaporated in air, the particles of vapor occupy the space between the particles of air. At any given atmospheric temperature and pressure, there is only a certain amount of space in the air for vapor particles. When all this space is occupied, the air is said to be "saturated" and evaporation ceases. The amount of heat necessary to change one gram of a liquid to vapor at the same temperature is called the "heat of vaporization." Heat of vaporization, like heat of fusion, is different for different substances. The amount of heat necessary to change 1 gram of water at 100° C. to steam at 100° C. is 540 calories.

(1) One factor which affects the rate of evaporation is the temperature of the liquid being evaporated. If this temperature is high enough for evaporation to be accompanied by the formation of bubbles of vapor in the liquid, the liquid is said to be "boiling." This temperature is called the "boiling point" of the liquid. The boiling point, like the freezing point, is different for different liquids. The boiling point of a liquid is affected by pressure. For instance, pure water will boil at 212° F. (100° C.) at sea level, whereas it will boil at a much lower temperature at high altitudes. This fact is one of the determining factors in the choice of coolants for modern airplanes. Another factor in the choice of a liquid for use in cooling systems is the fact that the boiling point of a liquid may be raised or lowered by mixing it with another liquid.

(2) Evaporation has a strong cooling effect, because of the heat absorbed in the process. This cooling effect is partly responsible for the formation of ice on aircraft.

e. Condensation.—Condensation is the change of state from vapor to liquid. During this process the same amount of heat is given off as is

absorbed when change from a liquid to a vapor takes place. Thus, in condensing, a gram of water vapor at 100° C. gives off 540 calories of heat. The temperature at which water vapor in the atmosphere condenses is called the "dew point." Rain, snow, and other forms of precipitation are forms of condensed (or condensed and solidified) water vapor in the atmosphere.

f. Sublimation.—Sublimation is the change of state directly from solid to vapor. It also is affected by temperature and pressure. Solid carbon dioxide, which passes directly from the solid to the gaseous state, illustrates the process. Some substances that sublimate, such as iodine, can be converted back from vapor to solid directly. Carbon dioxide must first pass through the liquid state.

Section III

ELEMENTS OF FLUIDS

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19. General.—A fluid is any substance made up of very small particles, or molecules, which have the ability to flow or move easily. This definition applies to both liquids and gases. Liquid and fluid are terms often used synonymously, but fluid has a much broader meaning. All liquids are fluids, but many fluids, such as air and other gases, are not liquids. Liquids and gases do not have the same distinguishing characteristics; nor do they follow the same rules of behavior. Since this is true, it is important to study the laws and principles applied to each.

20. Liquids.—The behavior of a liquid under various conditions is determined by its physical properties. Therefore, the physical properties determine the suitability of a liquid for some particular purpose. Among the most important physical properties of liquids are compressibility, thermal expansion, density, and specific gravity.

a. Compressibility.—When compressed, a fluid occupies a smaller space or volume than when not compressed. When compressed, it has a tendency to return to its original volume and therefore exerts an outward force in all directions. Certain substances, such as sponge rubber, offer little resistance to being pressed or squeezed into a smaller space. Other substances, such as iron, so strongly resist compression

that the reduction in volume is practically negligible. Liquids can be only slightly compressed; that is, the reduction of the volume which they occupy, even under extreme pressure, is very small. If a pressure of 100 pounds per square inch is applied to a body of water, the volume will decrease only three ten-thousandths of its original volume. Since other liquids behave in about the same way, liquids are usually considered incompressible.

b. Thermal expansion.—Liquids usually expand when heated. However, all liquids do not expand the same amount for a certain increase in temperature. If two flasks are placed in a heated vessel, and if one of these flasks is filled with water and the other with alcohol, it will be found that the alcohol expands much more than the water for the same rise of temperature. Kerosene and most oils expand more than water. Aircraft hydraulic systems, in which liquids are used, have provisions for compensating for this increase of volume in order to prevent breakage of the equipment.

c. Density.—The density of a substance is its weight per unit of volume. It may be expressed in pounds per cubic foot. The weight of water is 62.4 pounds per cubic foot. The weight of kerosene is only 50 pounds per cubic foot. Mercury, which weighs 849 pounds per cubic foot, has a much greater density than either kerosene or water. Iron has a density of 491 pounds per cubic foot. This is about eight times the density of water.

d. Specific gravity.—The specific gravity of a substance may be defined as the weight of a certain volume of the substance divided by the weight of an equal volume of water. The relation may be expressed as follows:

$$\text{Specific gravity} = \frac{\text{density of the substance}}{\text{density of water}}$$

Because it is plentiful, water has been chosen as a standard from which the specific gravities of other substances may be calculated. To simplify these calculations, the specific gravity of water has been set at unity, or 1. Specific gravities of other substances vary. Kerosene weighs 50 pounds per cubic foot, or eight-tenths the weight of water, and hence its specific gravity is 0.8; while mercury, which weighs 849 pounds per cubic foot, has a specific gravity of 13.5.

e. Measurement of specific gravity.—A body will sink until its weight is balanced by the weight of the liquid it displaces. Thus a piece of wood with a specific gravity of 0.7 will be submerged to seven-tenths of its volume when floating in water. This principle is used in the hydrometer, which consists of a large glass tube containing a weighted bulb. When a liquid is drawn into the lower

end of the tube, the bulb floats. If the density of the liquid is high, more of the bulb will project out of it than if the fluid were of low density. Since the weight of the bulb does not change, it can be graduated (marked with a scale), and the instrument can be used to compare the densities of liquids. Since the specific gravity of any liquid is determined by comparison of its density with that of water, the bulb is so graduated that it sinks to 1.000 in pure water, to values greater than 1.000 in liquids having densities less than water, and to values less than 1.000 in liquids having densities greater than water. Thus, the specific gravity of the electrolyte in a fully charged battery is found to be between 1.275 and 1.300. Any reading below this figure indicates that the battery is not completely charged.

21. Pressure production and transmission in liquids.—In discussing the production of pressure in liquids, it is necessary to deal with two distinct conditions—liquids at rest and liquids in motion. Certain reactions have been found to take place when pressure is applied to liquids at rest. These are commonly called "laws."

a. The most important of these laws is that confined liquids transmit pressure equally in all directions.

(1) If a jug or a bottle with a neck 1 square inch in cross-sectional area is filled with a liquid, and a force of 1 pound is exerted on a cork in the neck of the bottle, there will be a total force on the inner surface of the bottle equal to as many pounds as there are square inches of inner surface. Thus, if a force of 1 pound is exerted on the cork, and the area of the inner surface is equal to 50 square inches, there will be a force of 50 pounds exerted against the total inner surface. If the area of the inner surface is 150 square inches, the force will be 150 pounds, since the pressure is equally transmitted in all directions.

(2) By applications of this law, it is possible to produce tremendous forces in liquids by the use of pistons. The magnitude of these forces depends on the areas of the corresponding pistons. In figure 9, piston A has an area of ½ square inch at top and bottom. Piston B has an area of 10 square inches at top and bottom. The two are connected by a pipe the diameter of which is the same as that of piston A. When a 5-pound force is applied to the ½-square-inch piston, the produced pressure will be transmitted equally to an area of 10 square inches on the other piston. Since the surface of the large piston is 20 times that of the small piston, the 5-pound force is applied 20 times over that surface. This produces a force of 100 pounds. Of course, the same pressure is applied in all directions and is, therefore, equally transmitted over the other surfaces of the large cylinder. Where great pressures are involved, the piston walls must be built of such a material that they will resist the force produced by this pressure. In

figure 9, there has been a resultant force of 100 pounds produced from a 5-pound applied force.

b. Another law governing liquids at rest is that the pressure increases with the depth of the liquid. The total pressure on the bottom of a container filled with a liquid is equal to the weight of a column of that liquid which has the same bottom area as the bottom of the container and which is as high as the liquid is deep.

(1) For example, the total pressure on the bottom of a cylindrical container with a bottom area of 2 square feet and a height of 2 feet would be $2\times2\times62.4=249.6$ pounds (62.4 being the weight in pounds of 1 cubic foot of water). The pressure per square foot on the bottom would be one-half of 249.6 or 124.8 pounds and the pressure per square inch would be 124.8 divided by 144 or 0.86 pound (since 144 square inches equal 1 square foot).

(2) Assume that a can has several holes punched horizontally near the bottom and several other holes punched one above the other toward the top. When the can is filled with water, the flow from each hole at the bottom of the can will be the same, but the flow from the holes located one above the other will not be the same. The lower the hole, the stronger the flow, because of the greater weight of water, or pressure, above it. This example illustrates the fact that when no pressure is applied at the surface of a liquid, the pressure at any point in that liquid is dependent only on the depth and density of the liquid at that point (density being the weight of the liquid per unit of volume). The outward pressure against the walls of the container increases in direct proportion to the depth.

c. A combination of the laws given in *a* and *b* above brings about a useful and interesting result. If a small tube and a large tube, both filled with the same liquid, are connected to each other, the liquid will

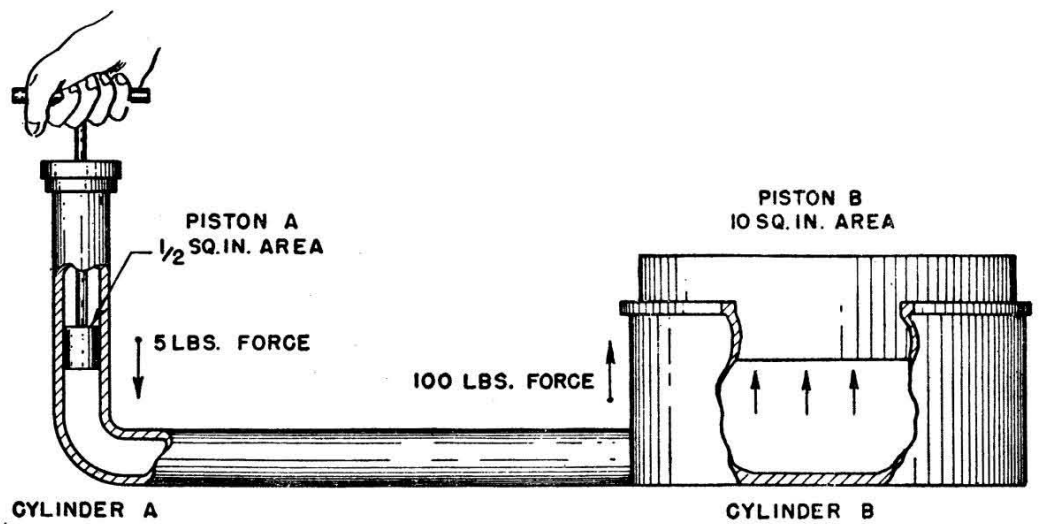


FIGURE 9.—Simple hydraulic mechanism.

remain at the same level in the small tube as in the large tube. Thus, water in the spout of a teakettle seeks the same height as the water in the kettle. For the same reason, the faucet of a water pipe connected to a standpipe of great height must be able to resist great pressure. If an ordinary wooden cask is filled with water and an upright steel pipe 1 square inch in cross-sectional area and 30 feet high, also filled with water, is connected to the sealed cask, the pressure on the inside surface of the cask will be very large, perhaps enough to burst the cask. The two laws of fluids at rest are in effect. The pressure at the lower end of the pipe is equal to the weight of 360 cubic inches of the liquid and is transmitted equally in all directions inside the cask, thus producing a total pressure the magnitude of which is dependent only on the height of the water in the pipe.

d. Most people have used the hydraulic jack, or applied the hydraulic automobile brake, with little thought of the principles by which they operate. A practical illustration of the hydraulic jack is shown in figure 9. A force of 50 pounds on the small piston the area of which is only ½ square inch will produce a force of 1,000 pounds on the larger piston, the area of which is 10 square inches. However, if a body weighing 1,000 pounds were to be raised by the large piston, the smaller piston would have to travel a distance of 10 inches to force the body up ½ inch, because the amount of liquid forced out by the small piston would be spread out over the large piston's surface of 10 square inches. Of course, when the small piston reached the bottom of the cylinder, the larger piston could not be moved higher. The apparatus shown in figure 9 would not be very useful, because a body could be raised only to a limited height. To make a more useful apparatus, a reservoir would have to be provided to supply the hydraulic fluid to be pumped to the larger piston, and check valves would have to be provided to regulate the transfer of the fluid.

e. In figure 10, a more practical hydraulic system is shown. The

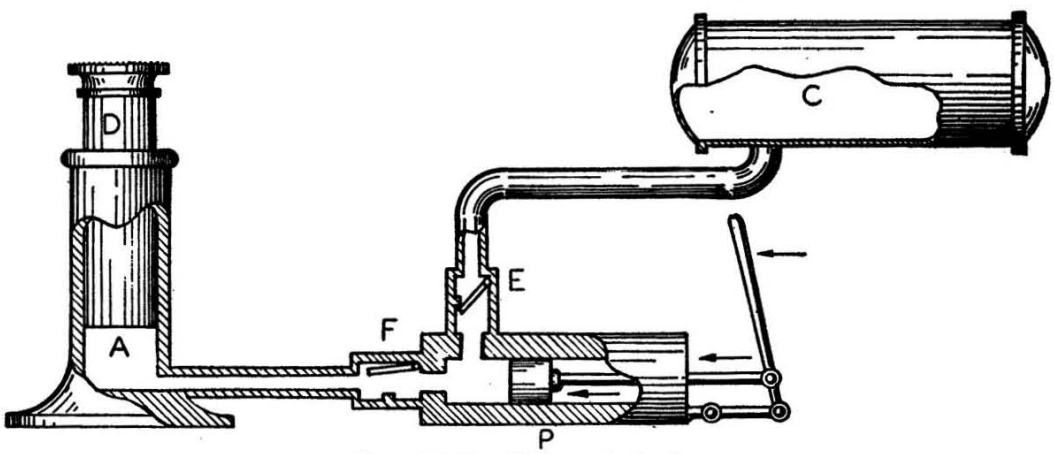


FIGURE 10.—Hydraulic jack.

hydraulic fluid is supplied from the reservoir C to the hand pump P, which forces the fluid into cylinder A. Valve F prevents the fluid that has been forced into the cylinder from returning, and valve E permits additional fluid to enter the pump and also prevents fluid which has entered the pump from being forced back into the reservoir. The pump can be operated until piston D has moved the desired height. The rate of movement of piston D will be determined by the rate at which the pump forces the fluid under it. The faster the fluid is forced into the cylinder, the faster the lifting rate will be. In aircraft, hydraulic systems are used for operating retractable landing gear, landing flaps, hydraulic brakes, and for many other mechanisms.

22. Gases.—*a. Definition.*—A gas is any substance in which the molecules (very small particles of which it is composed) are separated by relatively large spaces. We live at the bottom of an ocean of air which is a mixture of gases—mostly nitrogen, oxygen, carbon dioxide, and small amounts of other gases, including some water vapor. The principal difference between liquids and gases is that while liquids are almost incompressible, gases are very compressible because of the large spaces between the molecules.

b. Compressibility.—Gases not only are very compressible, but they expand much more than liquids when heat is applied. Although air is not ordinarily considered as a gas, it is a gas to which the gas laws may be applied. Since the particles of a gas are widely separated, even a slight pressure upon a confined gas will cause the particles to come closer together. Figure 11 is a simple illustration of the compressibility and elastic qualities of a gas.

c. Pressure-volume relation at constant temperature.—In figure 11, the pressure in a 12-inch cylinder with an airtight-fitting piston is 15 pounds per square inch. Suppose the piston is pushed down so that the gas is compressed into only 6 inches of the cylinder. None of the gas is lost in this process, but it is occupying only one-half the volume it occupied before. Hence the pressure on the inside of the cylinder is increased to 30 pounds per square inch, or just double the original pressure. Suppose that still more force is exerted on the piston, and the gas is compressed into 4 inches of the cylinder. The pressure of the gas on the inside becomes 45 pounds per square inch or three times as great as it was in the beginning, and the volume has decreased to one-third the original volume. In conclusion, it can be stated that the volume a gas occupies is in inverse proportion to the pressure exerted upon the gas, if the temperature remains constant.

d. Volume-temperature relationship at constant pressure.—In discussing figure 11, it was assumed that there was no change in the temperature of the gas. Actually, the volume of a given quantity of gas

and pressure on it are strongly affected by temperature changes. The lower the temperature of a given quantity of gas at a constant pressure, the smaller the space it will occupy. A gas will expand when heat is applied, as is obvious when a rubber balloon is placed over a heated stove. The gas or air inside the balloon will expand as its temperature is increased. In figure 12, notice that as the tempera-

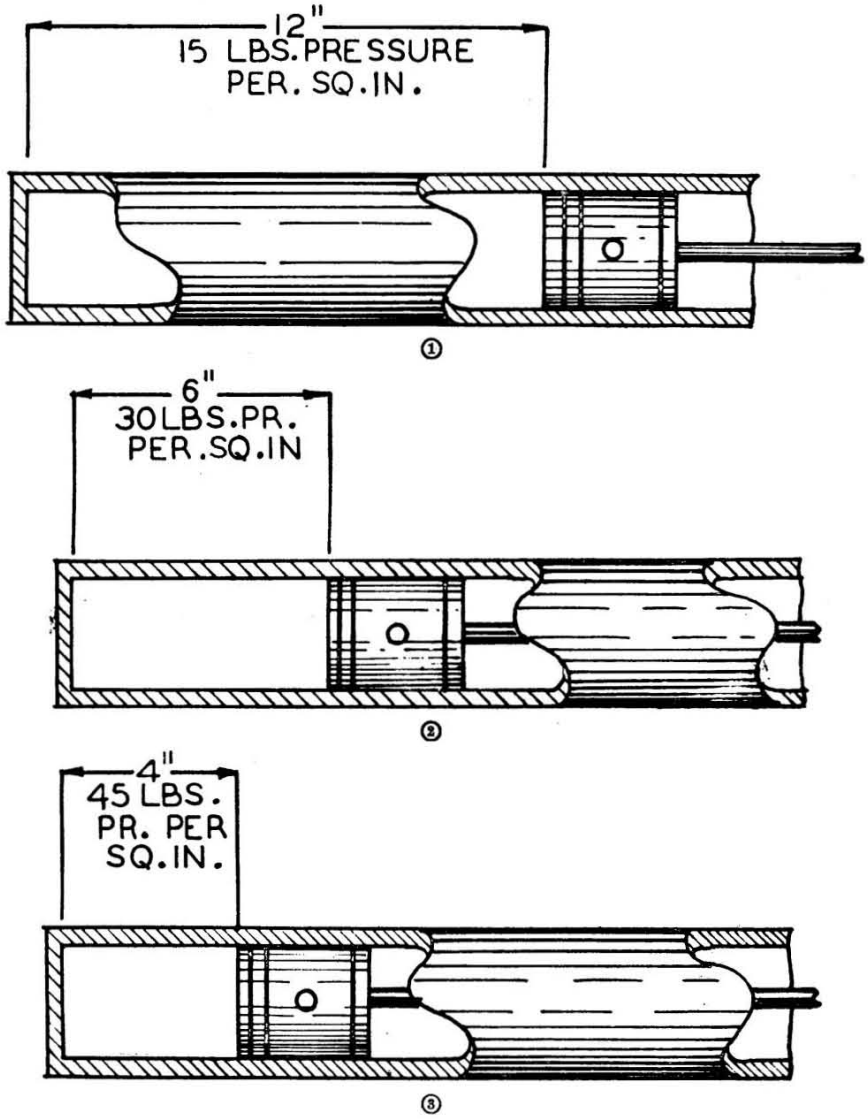


FIGURE 11.—Pressure-volume relationship of gases.

ture of the gas increases, the volume of the gas increases likewise. As the gas expands it pushes the piston back, until the pressure of the gas equals the pressure exerted by the piston. In this way the pressure inside the cylinder is kept constant at 15 pounds per square inch. In figure 12 ①, the gas takes up a space of 12 inches of the cylinder and has a pressure of 15 pounds per square inch at the prevailing temperature. As the temperature of the gas is increased

(fig. 12 ②) the piston moves back in the cylinder to compensate for an increase in volume of the gas. If the temperature is further increased, the volume will likewise increase (fig. 12 ③). It may be stated, therefore, that the volume of a gas will increase in direct proportion to the absolute temperature if the pressure remains the same.

e. Pressure-temperature relationship at constant volume.—Suppose that in figure 12 ② the piston had not been allowed to move back. The volume would tend to increase, but could not do so. Therefore, the pressure on the inside of the cylinder would increase. A further

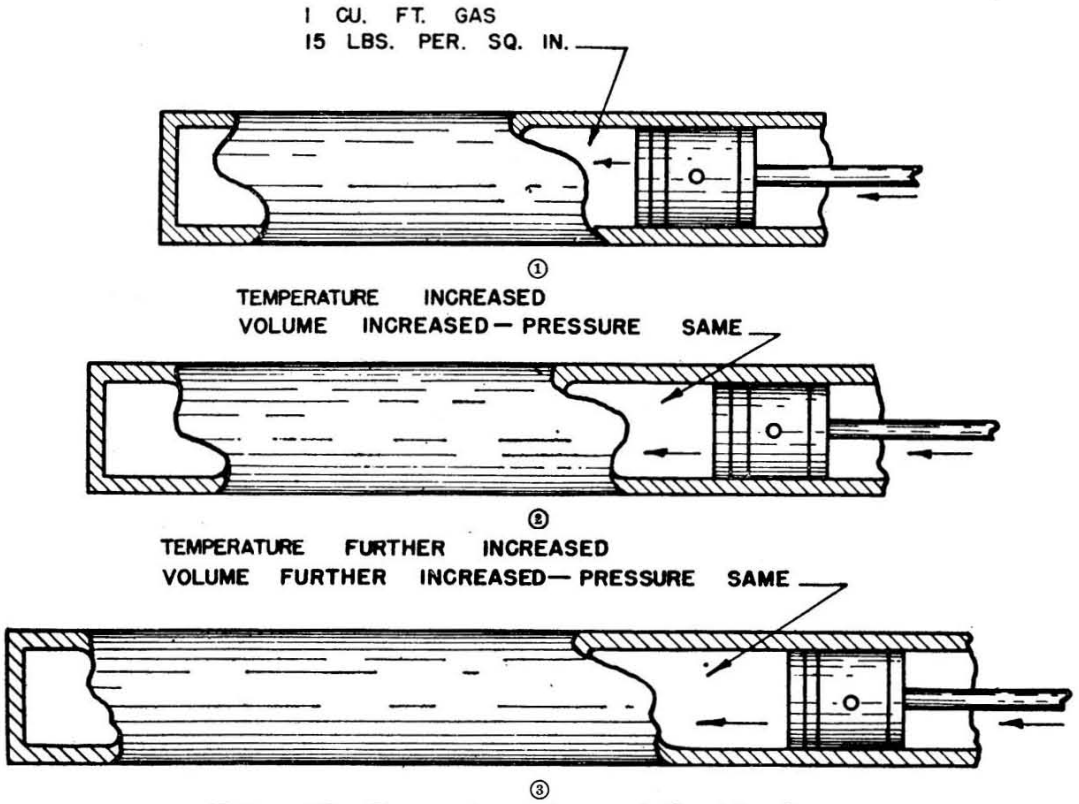


FIGURE 12.—Temperature-volume relationship of gases.

increase in temperature (with the piston held stationary) would cause an additional increase in pressure. It may be stated, therefore, that the pressure of a gas varies directly with its temperature when the volume of a gas remains constant. It should be remembered that when actual pressure or volume is being computed, absolute temperatures must be used.

23. Pressure production and transmission in gases.—The laws which govern pressure transmission in gases are essentially the same as those governing liquids. However, pressure transmission in gases will not take immediate effect. In figure 13, a great pressure can be produced by the piston in the cylinder of the pump as the

piston is suddenly moved downward. However, since gases are compressible, the pressure produced in the storage tank will not be equal to the pressure produced in the pump. Thus, if the pressure in the storage tank is 30 pounds per square inch, the pressure in the cylinder of the pump must be a little more than 30 pounds per square inch in order to force the gas into the tank. Suppose that when the piston is suddenly pushed down in the pump, a pressure of 35 pounds per square inch is applied to the valve D. This does not mean that there is a pressure of 35 pounds per square inch built up on the inside of the pressure tank; it will take several strokes of the piston to build the pressure inside the tank to 35 pounds per square inch. When a pressure of 35 pounds per square inch inside the tank is reached, it is necessary to apply a still greater pressure to the valve to force additional air into the tank. However, the pressure in the tank will be transmitted equally in all directions inside the tank.

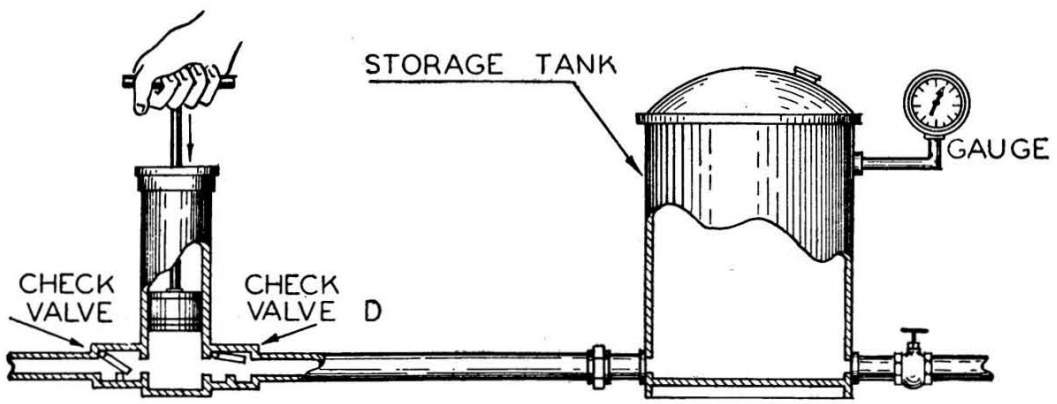


FIGURE 13.—Simple air pressure system.

24. Changes of state.—It is possible to increase the pressure of gas inside a storage tank to such an extent that the gas particles will be so compact that the gas becomes liquid. When this limit is reached, no more gas can be compressed into the storage tank, since liquids are practically incompressible. Great quantities of gas can be stored in a few cubic feet of space under such high pressure. The greater the pressure in the tank, the more dense the gas becomes. Only a few of the gases used in aircraft are compressed into a liquid state. In a carbon-dioxide cylinder, approximately three-fourths of the gas is changed into a liquid state, the remainder existing in a gaseous form in the upper part of the cylinder. When the cylinder valve is opened, the pressure of the gas forces the liquid out. As the liquid leaves the cylinder, the pressure decreases and the liquid changes to a gas.

25. Atmosphere.—*a. Definition and description.*—The atmosphere is the envelope of air surrounding the earth. This envelope of air extends to about 200 miles above the surface of the earth and is

deeper at the Equator than at the poles. The atmosphere is divided into two parts—the troposphere, or atmosphere below 36,000 feet, and the stratosphere, or upper portion of the atmosphere. The troposphere contains about three-fourths (by weight) of the total atmosphere. In the stratosphere, which consists of thinner air, the temperature is constant and only horizontal air currents occur, because of the rotation of the earth.

b. Composition.—Air is a mixture of gases, ordinarily consisting of approximately 21 parts oxygen and 78 parts nitrogen, plus very small parts of other gases, primarily water vapor and carbon dioxide. There is no chemical union between these gases, and the composition of air in open places remains almost constant.

c. Weight.—The weight of the gases which compose the atmosphere exerts a pressure against the surface of the earth. Thus, any area on the earth supports the weight of a column of air which extends above it for a distance of 200 miles, or the depth of the atmosphere. By direct measurement it has been found that an area of 1 square inch at sea level supports a vertical column of air that weighs 14.7 pounds. At higher altitudes this force is less because the column of air supported is shorter. Therefore, the pressure exerted by the weight of the atmosphere on any area grows correspondingly smaller with any increase in altitude above sea level, because of the lessened weight of the column of air that rises vertically above it.

d. Measurement of atmospheric pressure.—(1) Since air has weight, it exerts force against any surface immersed in it. A method of measuring atmospheric pressure is illustrated in figure 14. A tube nearly 3 feet long and closed at one end is filled with mercury. A dish is half filled with mercury. The open end of the tube is closed with the finger to prevent the escape of mercury, and the tube is inverted and placed with its open end below the surface of the mercury in the dish. Then the finger is withdrawn. The mercury in the tube sinks until it stands at a height of about 30 inches above the mercury level in the dish. Thus the pressure of the atmosphere on the mercury in the dish supports the column of mercury in the tube. If the procedure is performed at sea level, it will be found that the atmosphere, because of its weight, will support a column of mercury approximately 30 inches high. This is equivalent to a pressure of 14.7 pounds per square inch.

(2) If this tube of mercury with the dish is carried to a higher elevation, the level of the mercury in the tube will drop, because air pressure at higher altitudes is less than at lower altitudes.

(3) Instruments for the measurement of atmospheric pressure are known as "barometers." A tube of mercury or any other liquid is one

kind of barometer. Those in most common use employ an aneroid or pressure-sensitive capsule.

e. Variations of atmospheric pressure.—Air pressure is not constant, but the average daily variation in any locality is usually small. However, local conditions may cause relatively large variations over a larger area.

(1) Six factors may influence the condition of the atmosphere at any time or place: temperature, pressure, humidity, wind, clouds, and precipitation. The height of the mercury column of a barometer may

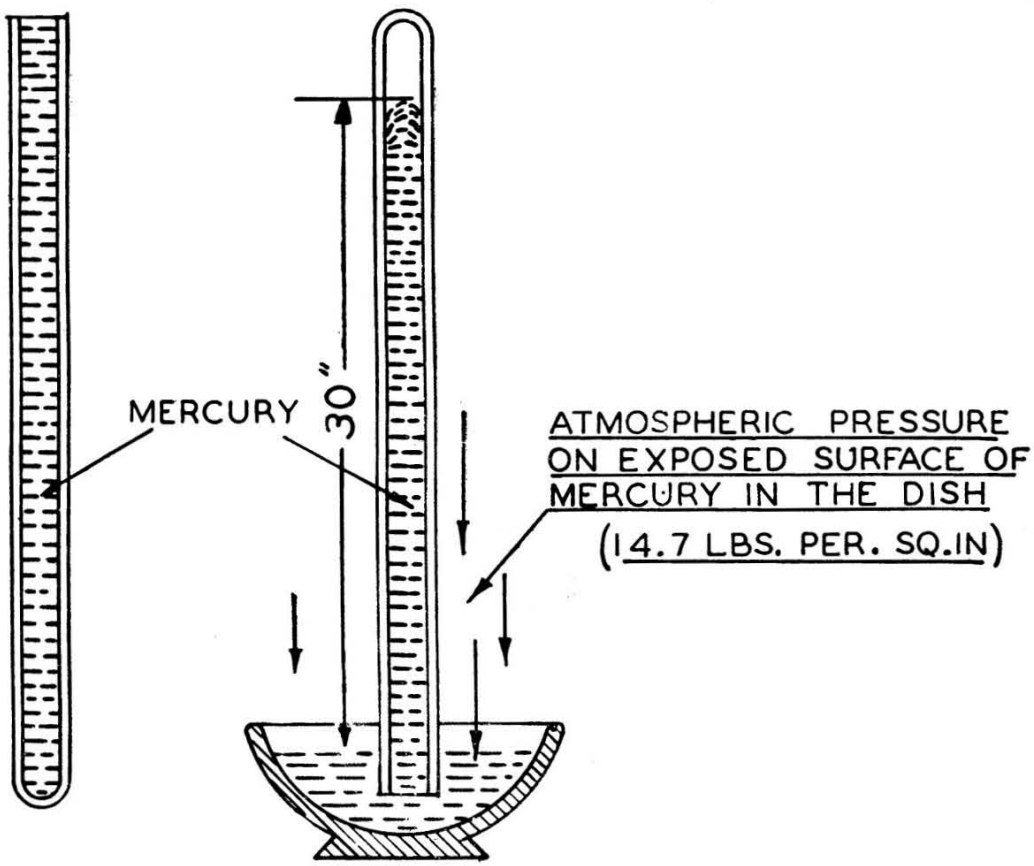


FIGURE 14.—Measurement of atmospheric pressure.

vary considerably in localities at the same elevation, the reason being that disturbances in the atmosphere affect the pressure at the earth's surface.

(2) It has been found that a low or rapidly falling atmospheric pressure is usually accompanied, or soon followed, by stormy conditions. Hence the barometer is of considerable importance in forecasting weather conditions some hours ahead, although weather forecasts are based only in part upon barometric readings.

f. Dew point and humidity.—(1) *Dew point.*—The temperature to which the atmosphere must be cooled in order that the water vapor within it may begin to condense is called the "dew point." At night

certain objects may lose heat more rapidly than others, and warm moist air may come in contact with them; then water vapor in the air is condensed and deposited on these objects. This moisture is dew. The dew point depends on the temperature, pressure, and humidity of the atmosphere.

(2) *Humidity.*—Humidity may be defined as the amount of water vapor present in the air at any one time. There is less than one-third of 1 percent (0.003) water vapor in the whole atmosphere, but conditions of pressure and temperature of the air at various places on the earth's surface may cause the air to contain as much water vapor as possible without its being precipitated. When such a condition occurs, the air is said to be "saturated." "Relative humidity" is the comparison of the amount of water vapor present in the air with the amount that would be present if the air were completely saturated, temperature and pressure remaining constant. If, at a given time, the air is only half saturated, the relative humidity would be 50 percent. Since humidity affects the occurrence of rain, snow, clouds, frost, etc., records of humidity are kept carefully for aeronautical purposes.

SECTION IV

ELEMENTARY AERODYNAMICS

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26. General.—*a. Resistance of air.*—The flight of an airplane depends on the fact that air has weight and substance, and therefore tends to resist the passage of any object through it. The manner in which an airplane is held up in the air (against the force of gravity) and is steered can be made clear by the use of simple illustrations.

(1) If a flat piece of cardboard is pulled rapidly through the air, flat side up and edge foremost, little air resistance is noticed. That is, the air particles are easily separated by the sharp edge. Now, if the leading (forward) edge of the cardboard is tilted upward slightly, more air resistance will be noticed when the cardboard is moved (because a greater area of cardboard opposes the air) and the cardboard will tend to rise as it moves forward. If the leading edge is now tilted downward, the cardboard will tend to move down-

ward as it moves forward. Finally, if the cardboard is held vertically and edge foremost, with the leading edge turned slightly sideward, when pulled forward the cardboard will tend to move sideward as well as forward.

(2) The reason for the deflection (upward or downward or sideward movement) of the cardboard when tilted slightly is a difference in the air resistance produced on opposite sides of the cardboard when it is moved. When it is tilted upward, greater air resistance is produced on the under side because this is the side opposing the air. On this side the air becomes denser (the particles move closer together) when the cardboard is moved against it; hence it exerts

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(For explanation of symbols, see FM 21–6.)

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